

## The role of thermal effects in constriction of positive column in inert gases

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### Introduction

Constriction, which is the fundamental phenomenon of gas discharge physics, has been attracting the attention of scientists for more than a century. However, scientists still discuss [1] what is the main mechanism that leads to a constriction. Two points of view have been formed by now on the mechanisms of constriction. On the one hand, inhomogeneous heating of the neutral gas can lead to a discharge constriction. Redistribution of neutral particles along the radius of the discharge tube due to the heating leads to an increase of the reduced electric field  $E/N$  at the discharge axis and its decrease at the periphery. This, in turn, leads to a compression of the ionization zone since the ionization frequency depends exponentially on the reduced electric field ( $I \propto \exp(-E/N)$ ,  $N$  – density of neutrals). On the other hand, discharge constriction may be associated with the features of the electron kinetics. The electron distribution function (EDF) along the radius of the discharge tube forms under competition between the frequencies of electron-atom and electron-electron collisions. As a result, due to an inhomogeneous distribution of charged particles, the EDF is depleted in the high-energy region along the radius. The ionization zone, which also depends on the ionization degree ( $I \propto \exp(-n/N)$ ,  $n$  – electron density), is compressed towards the discharge axis. Depending on the discharge conditions, one of these mechanisms may play a decisive role in the constriction of a discharge. The aim of this work is the experimental determination of the role of the inhomogeneous heating of the neutral particles during the constriction of a positive column of a glow discharge in neon and argon.

### Experimental study of the gas heating in neon and argon

The experimental setup is shown in Fig. 1. In order to separate the mechanism of inhomogeneous heating of the neutral gas and the mechanism associated with the peculiarities of the EDF formation, the discharge current was modulated by rectangular pulses. The duration of the discharge current pulse was set in order to provide the establishment of the ionization balance during the pulse, while the gas would not have time to significantly heat up. A large time interval between the pulses led to a complete cooling of the gas. The temperature field of a neutral gas was controlled by an interferometric method based on the Michelson interferometer.

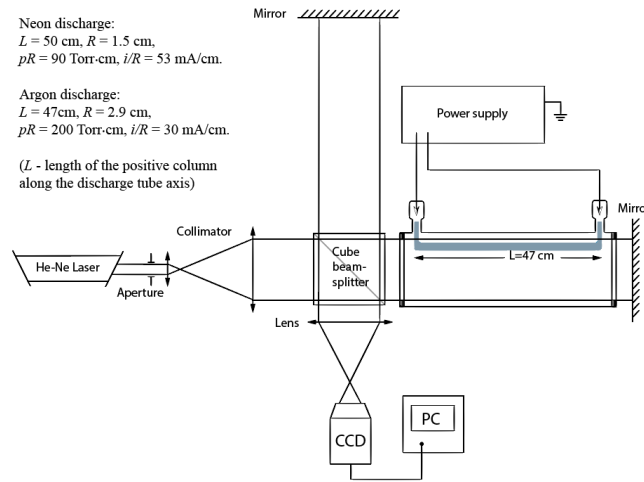


Fig. 1. The experimental setup.

An example of the observed interference patterns during the heating of the neutral gas in the stationary regime in neon and argon is shown in Fig. 2.

The experiment showed that in the short-pulsed regime in the absence of the inhomogeneous heating of the neutral gas a constricted cord is formed similar to a cord in a stationary discharge. Fig. 3(a) shows the radial distribution of light intensity for pulsed (black) and stationary (red) discharges in neon (triangles) and argon (dots). It can be seen that the profiles for the pulsed and stationary regimes almost completely coincide. At the same time, the cord in argon is noticeably narrower than in neon. Such difference is due to the peculiarities of the electron kinetics in these gases, in particular, due to the difference in the cross sections of elastic electron-atom collisions. The dynamics of heating and cooling of the neutral gas in the center of the constricted cord in neon in the short-pulsed (black) and stationary (red) regimes are shown in Fig. 3(b). Dots correspond to the results of the experiment and lines are the results of the numerical solution of the heat equation [2]. The pulsed regime made it possible to reduce the gas temperature at the center of the cord from 580 K to 370 K in comparison with a stationary discharge.

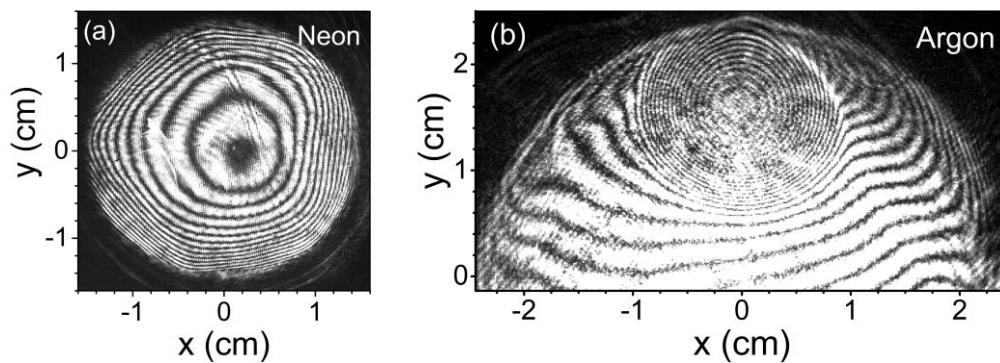


Fig. 2. Interference patterns formed during the inhomogeneous heating of the neutral gas in stationary regime in neon (a) and argon (b).

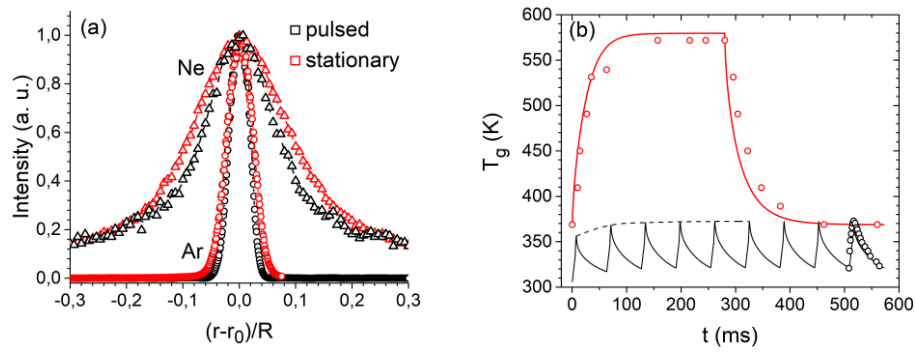


Fig. 3. (a) – radial distribution of light intensity in neon (triangles) and argon (dots) discharges in stationary (red) and pulsed (black) regimes; (b) – temporal dynamics of gas heating in the center of the plasma cord in neon in stationary (red) and pulsed (black) regimes. Lines - theory, dots - experiment.

Similarly, in argon, the gas temperature in the center of the cord was reduced from 1200 K in stationary regime to 400 K in pulsed regimes. The decrease of temperature can be also seen from Fig. 4 which presents the radial distribution of gas temperature in neon (a) and argon (b) for the stationary regime and for pulsed regime right before the end of the pulse of the discharge current. It is seen that the heating of the gas in argon is much stronger than in neon. At the same time, numerical results (lines) are in good agreement with the experimental results (dots).

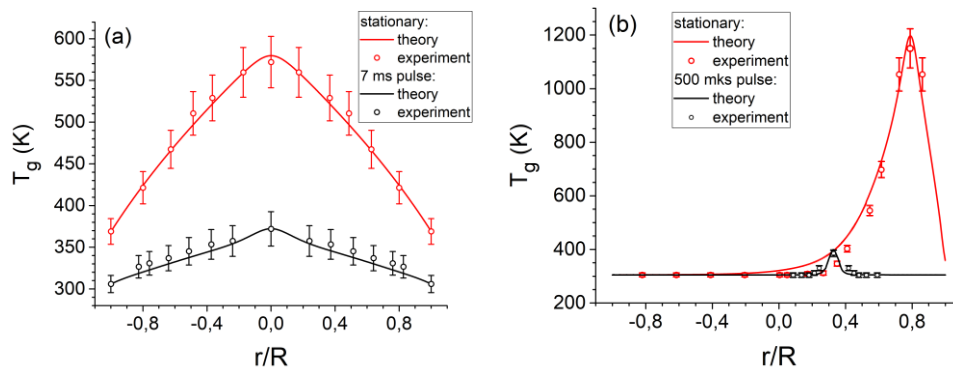


Fig. 4. Radial distribution of gas temperature in neon (a) and argon (b) for stationary (red) and pulsed (black) regimes. Lines – theory, dots – experiment.

Presented results show that the inhomogeneous heating of the neutral gas is not the main mechanism of constriction of a positive column in neon and argon. Thermal effects play a secondary role in the formation of the constricted cord. Nevertheless, the inhomogeneous gas heating in argon is much more pronounced than in neon as can be seen from Fig. 2(b) and Fig. 4(b). The gas heating leads to the emersion of the constricted cord due to the buoyancy force.

### Peculiarities of the gas heating in argon

Thermal effects in argon, observed as the emersion of a constricted cord towards the upper wall of the discharge tube with strong heating of the neutral gas, can be successfully

described by the joint solution of the Navier-Stokes equation (1) and the heat equation (2). These equations should be supplemented by the continuity equation (3), as well as the ideal gas law (4), which takes into account the increase of pressure during the gas heating. The system of equations can be written as follows [3]:

$$\rho \left( \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right) = \rho \vec{g} - \nabla p + \frac{1}{3} \mu \nabla (\nabla \cdot \vec{v}) + \mu \Delta \vec{v}, \quad (1)$$

$$\rho c_p \left( \frac{\partial T_g}{\partial t} + (\vec{v} \cdot \nabla) T_g \right) - \nabla \cdot (\kappa \nabla T_g) = jE, \quad (2)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \quad (3)$$

$$p = \rho R_{sp} T_g. \quad (4)$$

A comparison of the temporal dynamics of the neutral gas heating and the emersion of the constricted cord in the experiment and theory is shown in Fig. 5 (a-c) and (d-f), respectively.

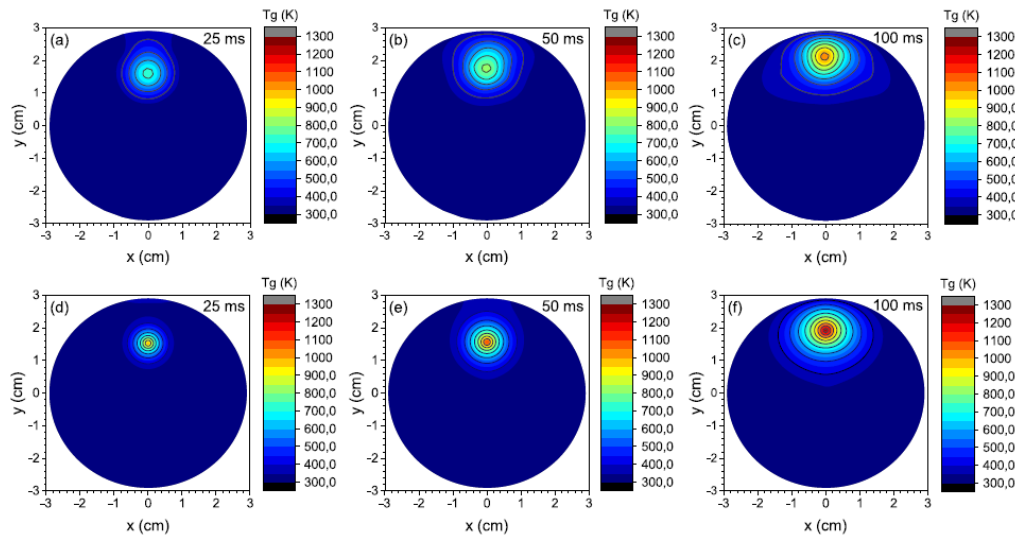


Fig. 5. Temporal dynamics of gas heating and plasma cord emersion according to the results of experiment (a)-(c) and theory (d)-(f) at the moments  $t=25$  ms,  $t=50$  ms and  $t=100$  ms (from left to right).

The presented figure shows a good agreement between the experimental and numerical results as in the absolute values of gas temperature as in the plasma cord location depending on time.

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## References

1. Ridenti M A, de Amorim J, Dal Pino A, Guerra V and Petrov G M 2018 *Phys. Rev. E* **97** 13201
2. Golubovskii Y B, Siasko A V, Kalanov D V and Nekuchaev V O 2018 *Plasma Sources Sci. Technol.* **27** 85009
3. Golubovskii Y B, Siasko A V and Nekuchaev V O 2019 *Plasma Sources Sci. Technol.* **28** 045007